Review of Electrical and Gravity Methods of Near-Surface Exploration for Groundwater

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ABSTRACT: The theory and practice of electrical and gravity methods of geophysics for groundwater exploration was reviewed with illustrations and data examples. With the goal of reducing cases of borehole/water-well failure attributed to the lack of the knowledge of the methods of geophysics for groundwater exploration and development, the paper reviews the basic concepts, field procedures for data acquisition, data processing, and interpretation as applied to the subject matter. Given a case study of groundwater exploration in University of Ilorin Campus, the three important techniques of electrical method of groundwater exploration are explained and illustrated using field data obtained in a previous study. Interpretation of resistivity data shows that an area measuring low resistivity (high conductivity), having thick pile of unconsolidated rock, and underlained by fracture crystalline is a 'bright spot' for citing borehole for groundwater abstraction in a basement complex area. Further to this, gravity method of groundwater exploration was discussed with field data from Wokbedilo community in Ethopia. Bouguer and reduced gravity anomaly results were presented as maps and contours to demonstrate how gravity data can be inverted to map groundwater aquifers and subsurface geological structures during groundwater exploration.

KEYWORDS: groundwater, gravity method, electrical method, aquifers, crystalline rocks

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I. INTRODUCTION

The use of geophysical methods for groundwater resource and water quality evaluation has increased dramatically over the last 15 years, especially in developing countries where the individual bears the responsibility of providing water for their daily activities. In every big city, dozen of new boreholes or hand-dug wells are drilled monthly in order to meet the demand for clean water. Subsequent to borehole/water-well drilling, pre-drill near-surface geophysical survey is done to identify a suitable place for borehole/water-well location. Despite the success of near-surface geophysical methods for groundwater exploration, cases of dry and failed boreholes and hand-dug wells are still being reported (Olorunfemi and Opadokun, 1987; Odoh *et al*., 2012). Borehole failure has been attributed to poor pre-drill geophysical survey, data mis-interpretation due to handlers' inexperience, and poor communication between geophysicists who handle the pre-drill geophysical survey and the drillers (Chaoka *et al*., 2006). Poor communication includes improper documentation of the findings of geophysical survey and the inability of the drillers to comprehend the details of the geophysical interpretations as shown in the report.

Given the economic loss and social deprivation associated with failed groundwater supply system, there is need to expose the basic science of groundwater exploration to non-geoscientist and other professional involved in groundwater development. Exposition of non-geoscientist involved in groundwater development to the science and practice of groundwater exploration can further reduce the risk of dry/failed boreholes and water-wells. For this reason, Water, Civil and Agricultural Engineers are the primary targets of this paper. While geoscientists deal with the search for groundwater, water chemists are concern with the study of groundwater quality and it's suitability for particular purposes. Civil and water engineers participate in borehole drilling and casing installation, dam and water flow channel construction. Agricultural Engineers has a responsibility to fabricate and install facility for irrigation and other agricultural uses. All the parties involved in the business of groundwater development require the basic knowledge of the science of groundwater exploration. Although this paper is concerned with the methods of finding groundwater- a primary responsibility of Geoscientist, the paper exposes other professionals in the business of groundwater development to the essential knowledge required to do checks and balances for a successful groundwater development project.

Groundwater application of near surface geophysics include mapping the depth and thickness of aquifers, delineating aquitards or confining units that may serve as barrier to groundwater flow, locating preferential fluid migration paths such as fractures and faults zones, identifying potential source of groundwater pollution such as salt water intrusion and leachates from industrial and municipal wastes (e.g., Olayinka and Barker, 1990; Jones, 1985). An aquifer is a geologic formation that contains sufficient saturated permeable material that can yield significant quantities of water to wells and boreholes. In essence, Groundwater exploration is all about the search for aquifers and structures that aid groundwater flow.

Theoretical and practical background to electrical and gravity methods of geophysics have been extensively reviewed by experts including Grant and West (1965), Dobrin (1976), Telford *et al*. (1976), Fetter (1980), Burger *et al*. (1992), McNeil (1980), Van Dongen and Woodhouse (1994), Parasnis (1979) among others. Many geophysical methods have been applied for the study of groundwater. Some show

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more success than the other. Gravity and magnetics have been used to map regional aquifers and large-scale basin structures for groundwater development (Carmichael and Henry 1977, Al-Garni, 2005, Levi *et al*., 2011). Electromagnetic and electrical methods have shown superior suitability for groundwater exploration because rock properties that are crucial to hydrogeology (permeability, porosity, and dissolved minerals) have direct correlation with electrical resistivity or electromagnetic conductivity. Electrical and gravity methods measure variation in the rocks' physical properties which depend on the rock matrix component, mineral type, pore spaces and size, and fluid content. Rocks exhibit different parameter-anomaly based on their physical properties, size of the target, depth of burial. The unique property of the target is an important factor that informed the choice of a geophysical method.

In this paper, electrical and gravity method of groundwater exploration are discussed with case histories from University of Ilorin Campus, Nigeria, and Wokbedilo Community of Ethiopia. Following the introductory section, the details of electrical and gravity methods are discussed in the respective order, with particular attention to field procedure for data acquisition, theory of the methods, data processing and interpretation. For electrical method, data used for illustration is from the author's thesis and published papers (Raji, 2005, Olasehinde and Raji, 2007, and lecture note). For Gravity method, data used for illustration is from a report by Levis *et al*. (2011). The report is in the public domain and thus gives permission for reproduction and redistribution with proper acknowledgement. This paper is a review of the electrical and gravity methods of geophysics as applied to groundwater exploration. Its main contribution is that it brings together, the experiences and scientific ideas scattered in published papers and textbooks that are not readily available to the audience/readership.

II. ELECTRICAL METHOD OF NEAR-SURFACE GEOPHYSICS

Electrical method of Geophysics is by far the most patronized geophysical method for groundwater exploration. This is partly due to the affordability of its equipment, and the simplicity of the method (Olasehinde and Raji, 2007). Being one of the earliest geophysical methods, it enjoys wide application for several geophysical studies ranging from down-hole measurement to near surface applications for groundwater exploration, groundwater contamination study, bedrock depth and topography measurement, salt water intrusion study, mineral exploration and quarry study, fracture depth and direction probing, post foundation study and road failure investigation, etc. There exist a direct correlation between electrical properties, geologic formations and rock fluid content (Zohdy *et al*, 1974; McNeill, 1980). Electrical method of groundwater survey is based on electrolytic conduction, where four metallic electrodes are coupled to the ground and connected to the resistivity meter (known as terrameter) through conducting wires (Figure 1). The two outer electrodes A and B introduce current to the rock formation; the two inner electrodes M and N measure the potential difference.

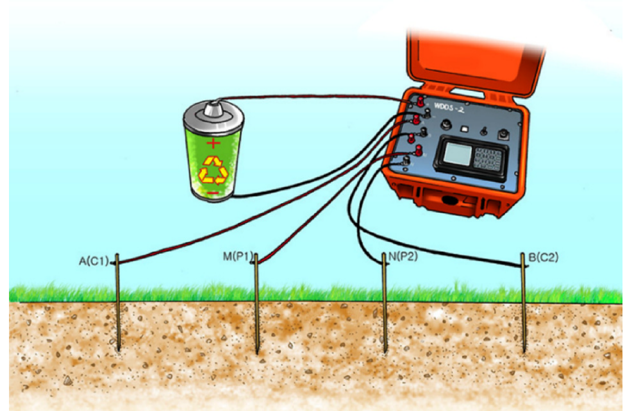

Figure 2: Equipment layout for electrical resistivity survey. (Image extracted from http://www.wtsgeo.com/index.php)

Resistivity meter measures the resistance a geological formation poses to the flow of current. The apparent resistivity of a geologic formation, P_a is defined as:

$$P_a = 2\pi \frac{V}{I} G \qquad (1)$$

where I is the current, V is the potential difference, and G is the geometric factor.

Geometric factor is dependent on the arrangement of the metallic electrodes, and the distances between the electrodes. The conductivity, ρ_e of a porous rock varies with the volume and arrangement of pore spaces, the amount and conductivity of contained water (Waxman and Thomas, 1974) as given in eqn (2).

$$P_e = a\Phi^{-m} S^{-n} \rho_w \qquad (2)$$

where Φ is fractional pore volume (porosity); S is the fraction of pores containing water, ρ_w is resistivity of water. The constant n equals 2; $0.5 \leq a \leq 2.5$; $1.3 \leq m \leq 2.5$.Variation in the properties of different rocks and the fluids within them give rise to different conductivity or resistivity signatures. In general, soil with high clay content and/or moisture will show higher conductivity than others. This is due to the presence of mineral particles that potentially carry electrical charges, and the presence of moisture that aids electrolytic conduction. Fractured consolidated rocks would measure lower resistivity than similar rocks with no fractures because fractures are potential paths for groundwater flow, and they usually harbour fluids. Contaminated water and saline water will show higher conductivity (or lower resistivity) compared to fresh water because they contain dissolves ions that aid electrical conductivity. The different techniques of electrical resistivity survey for groundwater include Vertical Electrical Sounding, Horizontal Resistivity Profiling and Azimuthal Electrical Resistivity Probing. Depending on the purpose of a survey and the complexity of the geology of the area, two of the three methods are often combined. Groundwater exploration usually starts with Horizontal Resistivity Probing (HRP) to study the lateral variation in the rock properties at near surface depth (usually less than 10m). Measured value of resistivity is plotted with horizontal distance. Locations with anomalous value (low resistivity, or high conductivity) along the profiles are marked for detailed study using Vertical Electrical

Sounding (VES) Technique. VES probes into deeper subsurface than HRP. As shown in Figure 2, the farther the separation between the current electrodes, the deeper the depth of penetration of the current introduced to the subsurface.

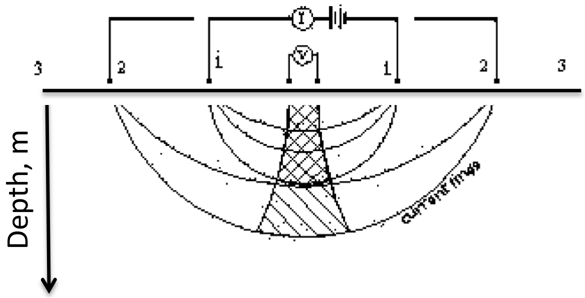

Figure 2: Schematic diagram of Vertical Electrical Sounding.

The rule of thumb is that the depth probed is, at best, about 40%-50% of the current electrode separation (Zhody *et al.*, 1974; Haberjam, 1975). The value decreases with complexity of the local geology. Measured resistivity is plotted with half of the current electrode separation. Azimuthal Electrical Probing (AEP) Technique is used to determine the presence, direction and depth of fractures in rocks. AER is used in combination with VES in crystalline rock terrains where fractures basement rocks are expected to be the source of groundwater aquifer. In AEP, resistivity is measured with depth at different angles (azimuth). Results are plotted with half electrode separation along different azimuth. Deviation from the radial structure (Figure 3a) indicates electrical resistivity anisotropy probably caused by the presence of fracture at subsurface. It shows equipotential surface where electrical resistivity in rock does not change with profile orientation - isotropy. Figures 3b and c show where resistivity changes with profile orientation- anisotropy.

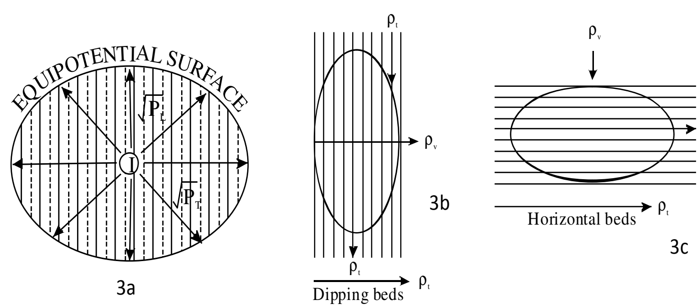

Figure 3: Electrical resistivity isotropy and anisotropy.

The direction of the long axis of the ellipse is taken to be the strike direction of the fracture. Koefoed (1970), Malik *et al* (1983), Jones (1985), Olorunfemi and Opadokun (1987), Van Overmeeren (1989), Olasehinde *et al.*, (1998), Olasehinde (1999), Raji (2005), Olasehinde and Raji (2007), Bayewu *et al.* (2012), Odoh *et al.* (2012) showed the use of electrical resistivity survey for delineating rock types, mapping boundary conditions and fractures in aquifer systems. Beeson and Jones (1988), Olayinka and Barker (1990), Hazell *et al.* (1992), Barker *et al.* (1992), Carruthers and Smith (1992), Al Garni (2004, 2005), Abubakar *et al.* (2014) demonstrated the applications of electrical techniques for siting wells and boreholes locations in crystalline basement aquifers in sub-Saharan Africa Countries. Ako, (1976), Olasehinde and Adelana (1999) applied electrical resistivity survey to the study of proposed dam sites.

Different rock layers give different electrical properties depending on the porosity, permeability, presence of moisture/water, and dissolved ions. Rock layers with high groundwater potential usually measure low resistivity (or high Conductivity). For such rock to be called an aquifer, it must be reasonably thick and porous to provide accommodation for water accumulation. Typically results of electrical method for groundwater study are presented in the form of profiles, curves and tables. The results can be interpreted using manual methods and computer algorithms (Orelana and Money, 1960; Olayinka and Mbachi, 1992) to deduce the number of geo-electric layer, thickness of each layer, the layer's resistivity, fracture depth and direction. In some cases the hydraulic conductivity and yield of the aquifer unit are also determined.

Other electrical methods rarely used for groundwater study include dipole-dipole method, Spontaneous potential method, magnetotelluric method, and electromagnetic method. Except electromagentic method, the other three methods are more suitable for Mineral exploration. Different technique has its peculiar electrode configuration or arrangement. All electrical methods of geophysics are limited to about 50m depth in crystalline rock terrain. Beyond this depth, results are less reliable. The limitations of electrical methods include suppression and equivalence. It is advisable that borehole or well log data around the study area is correlated with electrical resistivity data to guide interpretation, and reduce the risk of dry boreholes.

III. ELECTRICAL METHOD FOR GROUNDWATER EXPLORATION – A CASE STUDY

To add values to the description of electrical method of groundwater exploration, I present a case study (Raji, 2005; Olasehinde and Raji, 2007) of groundwater exploration in a part of the basement complex of Nigeria- University of Ilorin Campus, Ilorin. The rock types in the area include Banded Gneiss, Granite Gneiss, Augen Gneiss, Granodiorite, Microgranite, Pegmatite and Quart Vein. These rocks are in places covered by loose unconsolidated rocks formed by in situ weathering. In other places, crystalline rocks outcrop to the surface. Structural elements in the area include fold, joints, foliation and banding. Groundwater exploration study in the areas involved the use of the combination of Electrical Resistivity Profiling, Vertical Electrical Sounding, and Azimuthal Electrical Probing to identify suitable areas for citing boreholes for groundwater development. The exploration programme began with Horizontal Resistivity Profiling. 16 resistivity profiles of various lengths were traversed covering some parts of the University Quarters, University Dam, Faculty of Agriculture, Works Department, and the students' hostel. Profile length range from 200 m to 320 m. Resistivity values plotted with distance for one of the profiles is shown in Figure 4 for the 15 m and 30m station intervals. Based on the HRP results from the 16 profiles, 23 locations were selected for detailed study using Vertical Electrical sounding of Schlumberger array.

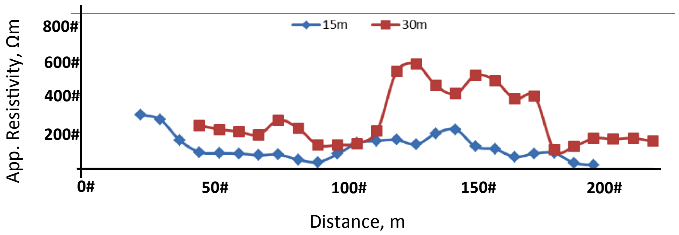

Figure 4: Horizontal resistivity plotted with distance for the profile covering the University Primary School junction.

The VES curve for a location around 180 m along the profile covering the university primary school junction is shown in Figure 5. This curve and the others were interpreted manually using master curves, and later using computer iteration method. The black line is the curve from the smoothed data. Using master curve and computer iteration method, 3 geo-electric layers are interpreted from this curve.

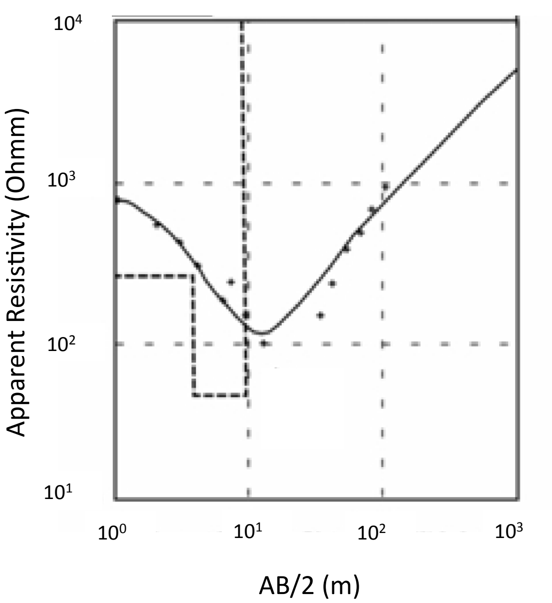

Figure 5: VES curve from the Vertical Electrical Sounding at distance 90 m along the profile shown in Figure 4.

At the final stage of the exploration study, Azimuthal Electrical Probing is applied to 8 locations (distance 90m, and other not shown here) to determine the depths and directions of fractures. The resistivity polygon computed from the Azimuthal Electrical Probing of distance 90m on figure 4 is presented in Figure 6. The polygon shows two episodes of fractures: a northwest - southeast trending fracture at shallow depth, and a northeast-southwest trending fracture at greater depth. This fracture is suspected to be responsible for the very low resistivity at AB/2 of about 15m in Figure 5. Finally, electrical resistivity pseudo-sections are computed for this profile. The pseudo-section shows the number of layers, thickness of each geo-electric layers and their resistivities. Putting together the results of the different techniques and their interpretations, places around 90m and 180m were recommended for borehole drilling. In this study, the selection of an area for groundwater development (e.g., borehole/well siting) is informed by the presence of low resistivity, presence of thick unconsolidated/weathered rocks and fractures. These three elements are the essential indicators of aquifers system in a crystalline rock terrain.

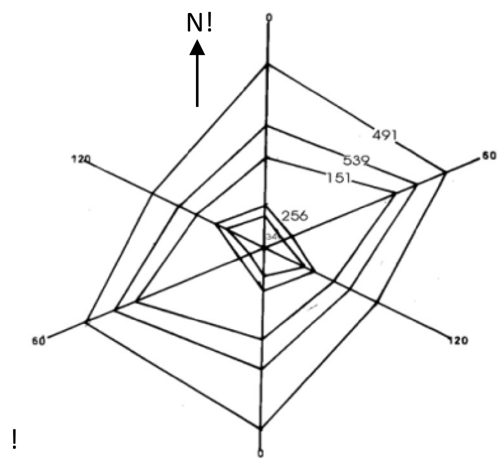

Figure 6: Azimuthal Electrical Probing results showing two episodes of fractures around location 90 m.

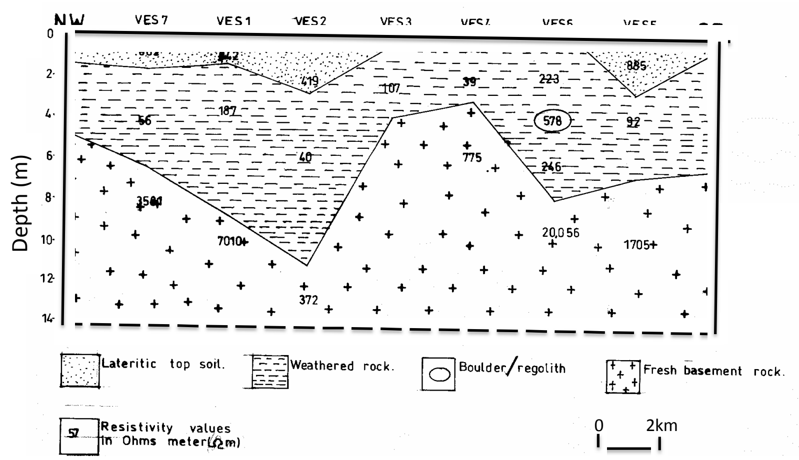

Figure 7: Geo-electric cross-section distance around 90m in blue arrow, VES2. Cross-section shows the number of geo-electric layers, thickness and depth of each geo-electric layer and their resistivities.

IV. GRAVITY METHOD FOR GROUNDWATER EXPLORATION

Gravity method of geophysics measures difference in the Earth's gravitational field at specific location due to the rock mass property. The method is suitable for near surface groundwater exploration in areas where poorly-consolidated/unconsolidated low-density rock overlies denser Precambrian basement rocks. Because gravity is directly related to mass, the difference between the two rock masses will produce noticeable anomaly in the earth's gravity field. If the anomaly is properly measured, it can be used to estimate the thickness of the unconsolidated rock (Chandler, 1994). In crystalline rock terrain, unconsolidated rock usually forms groundwater aquifer because of their high porosity, permeability and transmissivity. The bulk density, ρ_{sm} of a fluid saturated rock is defines as

$$\rho_{sm} = \rho_r\left(1-\frac{\rho_{\%}}{100}\right)+{\rho_{\%}}/{100} \tag{3}$$

Mass of the rock, $m = \rho_{sm}v$ where ρ_r is the density of the rock, $\rho_{\%}$ is the percentage porosity, and v is the volume.

The gravitational effect, F of the earth on such rock can be defined as:

$$F = \frac{GmM}{R^2} \tag{4}$$

Where M and R are the mass and radius of the earth respectively, G is the universal gravitational constant, and m is the mass of the rock. The higher the mass of a rock, the higher the gravity effect of the body. Unconsolidated rocks are potential aquifers for groundwater because of their high porosity and permeability. They usually have lower density and hence posses lower gravity values compared to denser Precambrian rocks.

Gravity survey has been used (sometime in combination with other methods of geophysics) to study bedrock topography underlying unconsolidated aquifer, buried basement channel in crystalline rock terrain, buried alluvium aquifers in tropical areas, basin fill aquifers in arid regions, to determine water table levels, and for locating structural features that are critical for groundwater accumulation and flow (Ibrahim and Hinze, 1972; Carmichael and Henry, 1977; Van overmeeren, 1975; 1981; Cornwell and Carruthers, 1985; Allis and Hunt, 1986, Telford *et al*., 1990; Adams and Hinze, 1990; Lewis *et al*., 2011). Gravity data for groundwater study are usually acquired on grids or profiles depending on the scale of the survey and size of the target, using high precision gravimeter. Gravity is measured using gravimeter; its unit is Gal (m/s^2).

During data acquisition, a base station is established. At regular interval, the field crew will have to return to the base station to take measurements, or keep another gravimeter in the base station to take gravity measurements at specified time interval, in order to measure the tidal effect on gravity values. Data acquired by gravimeters is known as observed data. Observed data is usually corrected for instrument drift and tidal effect. In addition to this, the data is subjected to latitude correction, terrain correction, free-air correction, and bouguer correction (Cogbill, 1990, Telford *et al*., 1990; Burger *et al*., 1992). Figure 8 shows the effect of gravity correction on bouguer gravity anomaly. Bouguer gravity anomaly, Δg_B can be described as:

$$\Delta g_B = g_{obs} + FA_{corr} - B_{corr} + T_{corr} \tag{5}$$

where g_{obs} is the measured data, FA_{corr} is the free air correction, B_{corr} is the bouguer correction, and T_{corr} is the terrain correction.

The gravity data obtained after these corrections is known as bouguer gravity anomaly. Bouguer gravity anomaly is usually presented in form of maps or contour lines or both. To interpret the subsurface sources causing the Bouguer gravity

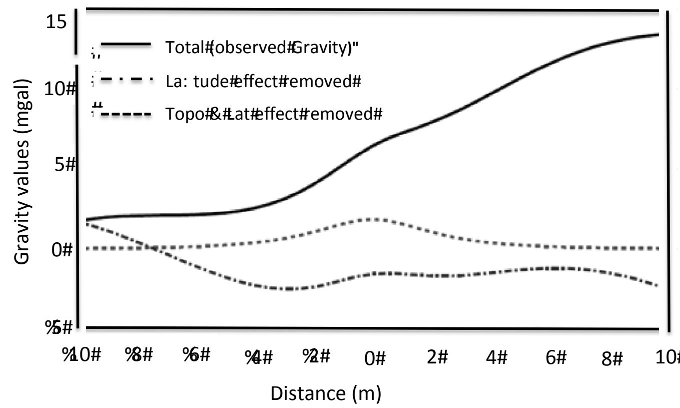

Figure 8: Importance of gravity correction. Thickline - gravity reading plotted with distance for observed gravity anomaly, dashline – after latitude effect is removed from the observed anomaly, dotline - after topographic/terrain effect is removed from the observed anomaly.

anomaly, regional gravity value is usually subtracted from the bourguer anomaly to obtain residual gravity anomaly. The separation can be done using manual approach, computer methods, or both (Fajklewicz, 1976; Butler, 1984a & b; Cady, J. W., 1980). The residual gravity anomaly can then be modeled by computer methods (Cady, 1980; Telford *et al*., 1990) to determine the depth and geometry of the source of the anomaly.

V. Gravity Method for Groundwater Exploration - A Case Study

Gravity survey for groundwater exploration in Wokbedilo (Lewi *et al*., 2011) is presented as a case study. Wobekdilo, a part of Borena zone, is located in the southern part of Ethopia. Gravity survey for groundwater exploration was carried out with the aim of identifying places suitable for citing boreholes. The study area was divided into grid points. High precision gravimeter was used to acquire gravity data at every grid point, and a differential GPS was used to measure the coordinates of data points. At regular interval, base station is reoccupied to measure changes in tidal effects. Data acquired was corrected for instrumental drift, tidal effects, free-air correction, bouguer correction, latitude correction and terrain correction. The bourger anomaly computed for the study area is presented in form of a map in Figure 9.

Further to this, regional gravity anomaly is subtracted from the bourger gravity anomaly to obtain the residual gravity anomaly as presented in Figure 10. The residual gravity anomaly was interpreted (Lewis *et al*., 2011) to delineate locations that are suitable for borehole drilling. The two places recommended for drilling are indicated by stars in Figure 11, modified from Lewis *et al*., 2011. Geological interpretation and the geometry of the body causing the gravity anomaly is shown in figure 10. One of the boreholes drilled in this area has a yield of 22 litres per minute.

VI. DISCUSSION AND CONCLUSION

The theory and practice of electrical and gravity methods of

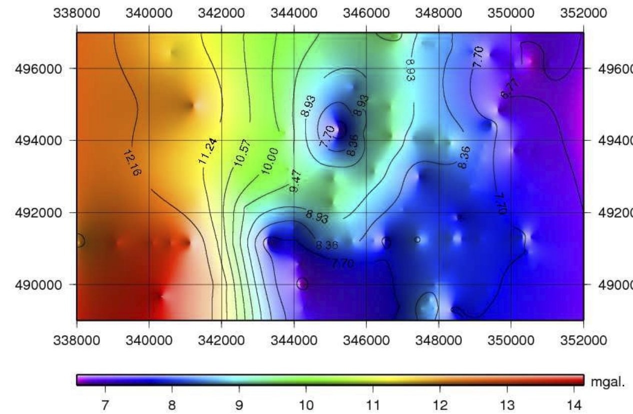

Figure 9: Bouguer gravity anomaly map from groundwater exploration data at Wobekdilo (Lewis *et al*., 2011).

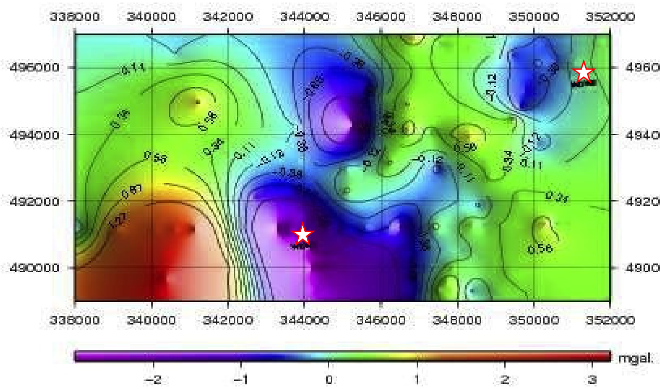

Figure 10: Reduced gravity anomaly map for Wokbedilo. (Lewis *et al*., 2011).

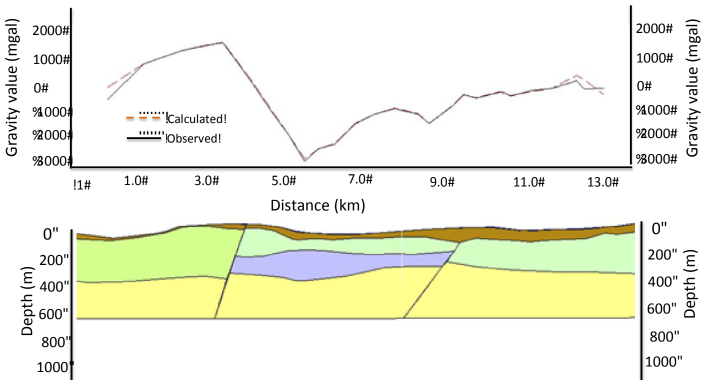

Figure 11: Cross-section and geological model interpreted from the reduced/corrected gravity anomaly for one of the places recommended for borehole citing at longitude 344000 and longitude.

geophysics for groundwater exploration are discussed with data examples. Starting from field procedure for data acquisition to data processing, results presentation and interpretation, this paper explains the nitty-gritty of the selected methods and the techniques required for successful groundwater exploration. The unique selling point of the paper is that it brings together, in one single piece, the essential knowledge and field data, experiences, and scientific ideas of the subject matter from several published geophysics paper, scientific reports and textbooks that are not readily available to the intended readership. The review and the explanation provided in this paper can be followed to carry out successful groundwater exploration. The objective of the paper is to equip water and civil engineers, agricultural engineers and 'new comers' geoscientists with the knowledge required for successful groundwater exploration and development. It is hoped that the circulation of this paper will reduce cases of borehole and water-well failure attributed to the lack of knowledge of the geophysical methods.

Following the introductory section, the two methods of near-surface geophysics for groundwater exploration, namely electrical method and gravity method are reviewed and illustrated with data examples from a University of Ilorin Campus and Wokbedilo Community of Ethiopia.

Electrical method measures the resistance a rock unit poses to the free flow of electric current. The presence of water in a rock unit is expected to reduce the resistivity and increase the conductivity properties of rocks. The three techniques of electrical method discussed are Horizontal Resistivity Profiling (HRP), Vertical Electrical Sounding (VES) and Azimuthal Resistivity Profiling (ARP). HRP is most suited for very shallow resistivity profiling during reconnaissance geophysical survey. Its result can be used to elucidate lateral variation in rock resistivity, delineate geological boundaries, lateral extent of shallow fractures, faults, and aquifers. VES gives indication of the changes in the electrical properties of rock with depth. The method is widely used for locating the depth and vertical position of different geological units, for example, the depth and thickness of an aquifer. ARP is most suited for fracture/fault mapping, especially in the determination of fracture depth and direction. The paper also detailed the successive order of combining the three methods and interpreting their results.

Following this, gravity method of groundwater exploration is reviewed. Subtle gravity difference between loose semi-arid sediments and the crystalline bedrock was mapped to explore groundwater potential of Wokbedilo Community of Ethiopia. Gravity data acquired in the area was subjected to various corrections and regional reduction in order to extract the gravity anomaly that is due to density contrast between the semi-arid sediments (aquifer) and the bedrock (Lewis, *et al*, 2012). Interpretation of the reduced gravity anomaly suggested two areas that are suitable for borehole drilling. Model and structural interpretations of the anomaly showed that the aquifer system in the area is enhanced by the presence of a normal fault.

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